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ROTATIONAL LOADING OF DOUBLE-BRAID LINE EYE SPLICES.(U)
JUN 82 K R BITTING
UNCLASSIFIED CGR/DC-12/82 USCG-D-27-82 NL

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16. Abstract
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The results of these tests shown that the strength of a line with the Red Book eye splice is not reduced when loaded in rotational loading; both legs of the splice are equal in strength. The weakness in one leg of the Blue Book splice is confirmed; it fails in rotational loading when the load in the standing part of the line reaches 62% of rated break strength (RBS).

The Red Book splice is approximately 9.8% stronger than the Blue Book splice in straight-pull conditions (i.e. no rotation).

Nylon 3-strand twisted line is included for comparison with double-braid line. Results indicate that one leg of the eye fails in rotational loading when the load in the line reaches 81% RBS because the tucks in the splice fail and the splice pulls apart freeing the end of the leg.

* Navy Training Course, Boatswain's Mate 3 & 2, NAVPERS 10121-D, Third Edition, 1964
** Navy Training Course, Boatswain's Mate 3 & 2, NAVPERS 10121-G, 1981

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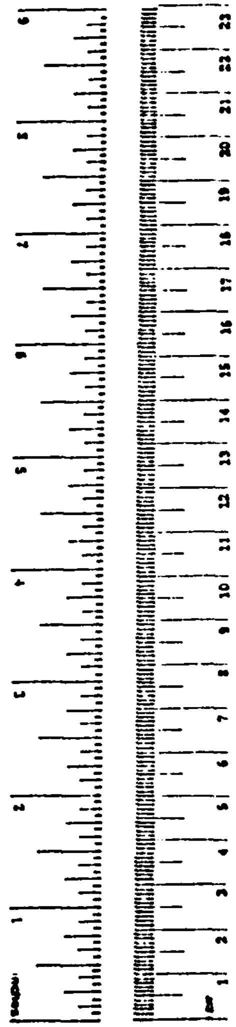
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

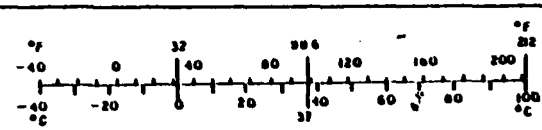
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 OBJECTIVE AND SUMMARY

To determine the strength of the legs of an eye splice in double-braid line under tension when the eye is rotated around a bollard.

Summary

Two different splicing methods for double-braid line have been tested to simulate a loading condition in which the eye of a line under tension is rotated around a bollard as might occur during a docking operation. The Blue Book splice method, used on double-braid line before 1976, is thought to have one leg of the eye that is significantly weaker than the other. The Red Book splice method, a revision of the Blue Book, is thought to eliminate the weakness of the Blue Book splice.

The results of these tests show that the strength of a line with the Red Book eye splice is as strong in rotational loading as it is in straight pull conditions. Both legs of the splice are equal in strength. The weakness of one leg of the Blue Book splice is confirmed; it fails in rotational loading when the load in the standing part of the line reaches 62% of rated break strength (RBS).

The Red Book splice is approximately 9.8% stronger than the Blue Book splice in straight-pull conditions (i.e. no rotation).

Nylon 3-strand twisted line is included for comparison with double-braid line. Results indicate that one leg of the eye fails in rotational loading when the load in the line reaches 81% RBS because the tucks in the splice fail and the splice pulls apart freeing the end of the leg.

During rotational loading, the ratio of the load in the high-tension leg to the low tension leg does not appear to exceed 3:1. This is much lower than suggested by other investigators.

When failure occurs in the leg of an eye, the end of the line recoils around the bollard and covers a very wide snapback path. When failure occurs near the taper of the splice, the line recoils along a very narrow path.

2.0 BACKGROUND

2.1 Operational Conditions Being Simulated

Synthetic lines are used to control the position of a ship as it is being maneuvered alongside a dock or into a mooring. During these operations an eye in one end of the synthetic mooring line is often placed over a bollard on the pier and the other end is taken on deck where the line handlers can coordinate with the bridge for effective use of the line during the operation. Some lines, such as spring lines, can have high loads applied to them when the ship's engines are engaged to steam on the line to move the ship closer to the dock. High loads can also result when wind forces, for instance, apply unexpected force to the ship causing it to swing around the bollard on the pier. These tensions, combined with the friction between the line and the bollard, produce large tractive forces between the eye and bollard. As the ship swings around the bollard, the eye cannot slide around

the bollard to equalize the tension in both legs of the eye. The result is a much higher tension in one leg than in the other. If the leg receiving the tension is significantly weaker than the standing part of the line, failure will occur at a load much lower than the expected strength of the line.

The use of double-braid line in these situations is thought to be the cause of several accidents in which one leg of the eye fails and the line causes serious injury or death of personnel standing in the recoil path. The Blue Book splice used on double-braid line before 1976 has one leg that is thought to be significantly weaker than the other. The Navy became concerned about the number of accidents involving this particular problem and collaborated with the Coast Guard to determine the strength of the Blue Book splice in rotational loading and to also test the revised splicing method, the Red Book splice. This study is in response to this joint Coast Guard and Navy need.

2.2 Double-Braid Eye Splice Techniques and Terminology

Two double-braid line splicing techniques have been in use. The early technique, called the Blue Book splice (ref. 1), requires that the core be cut off at a point near the throat of the splice (Figure 2-1). This effectively leaves only the cover of the line to carry the load in that area. Under rotating load conditions, the eye fails in this area at loads that are thought to be significantly less than the strength of the standing part of the line.

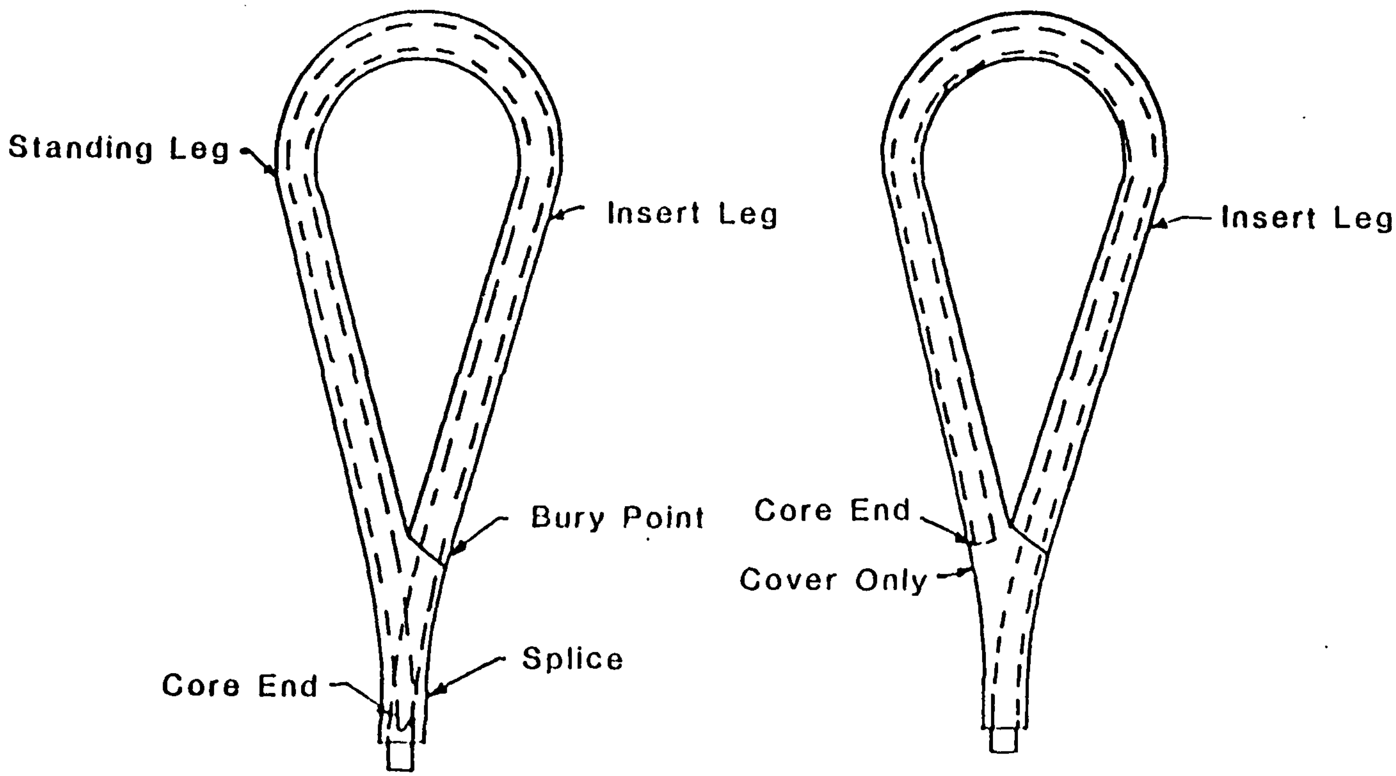
In 1976 a modification was made to the splicing technique which requires inserting the tapered end of the core back into the splice area (Figure 2-1) to increase the strength of the splice in the throat area. This technique, subsequently distributed in a booklet with a Red cover, has come to be called the Red Book splice (ref. 2). It is thought that this technique increases the strength of the eye and eliminates the weakness of the Blue Book splice.

Parts of the eye and line are given the following names to facilitate discussion in the rest of the report. This nomenclature refers to the appearance of the eye from the outside and does not refer to steps taken in making the splice (i.e., inserting core in cover, crossover point, etc.) or the final arrangement of the core inside the line. Refer to Figure 2-1.

Standing part of the line: The part of the line not in the eye or splice.

Standing leg: Appears to be a continuation of the standing part of the line.

Insert leg: Appears to be inserted into the line to form the eye.



Red Book Splice | Blue Book Splice

FIGURE 2-1 DOUBLE-BRAID EYE SPLICE

3.0 CALCULATION OF THE TENSION IN THE LEGS OF AN EYE

The force diagram of an eye around a bollard of radius, R, is shown in Figure 3-1 (a). As the standing part of the line under tension, T_R, is rotated around the bollard through an angle, γ, the tension in one leg of the eye, T_1, increases and the other, T_2, decreases. The eye is in contact with the bollard over the wrap angle, $\Pi-2\Theta$. The force in the legs, T_1 and T_2, may be calculated from the geometric relationship between the eye and the standing part of the line independent of bollard friction. The free body diagram in Figure 3-1(b) shows the relationship of the line to the eye legs.

From the Law of Sines,

$$\frac{T_R}{\sin A} = \frac{T_1}{\sin(\Theta + \gamma)} \qquad \text{(IV-1)}$$

$$\angle A-(\Theta-\gamma) + (\Theta-\gamma) = \Pi$$

Therefore,

$$\angle A = \Pi - 2\Theta$$

Equation (IV-1) becomes

$$T_1 = T_R \frac{\sin(\Theta-\gamma)}{\sin(\Pi-2\Theta)} \qquad \text{(IV-2)}$$

Similarly,

$$\frac{T}{\sin(\Pi-2\Theta)} = \frac{T_2}{\sin(\Theta-\gamma)}$$

or

$$T_2 = T_R \frac{\sin(\Theta-\gamma)}{\sin(\Pi-2\Theta)} \qquad \text{(IV-3)}$$

Therefore, the tension in the eye legs, T_1 and T_2, can be calculated by knowing the tension in the line, T_R, the angle of rotation of the line around the bollard, γ and contact angle, Θ.

The coefficient of friction, μ, of the bollard can also be calculated very easily. It is given by the equation (ref. 3).

$$\mu = \frac{1}{\alpha} \ln\left(\frac{T_1}{T_2}\right) \qquad \text{(IV-4)}$$

where α is the angle of wrap of the eye around the bollard. From Figure 3-1(a), $\alpha = \Pi-2\Theta$.

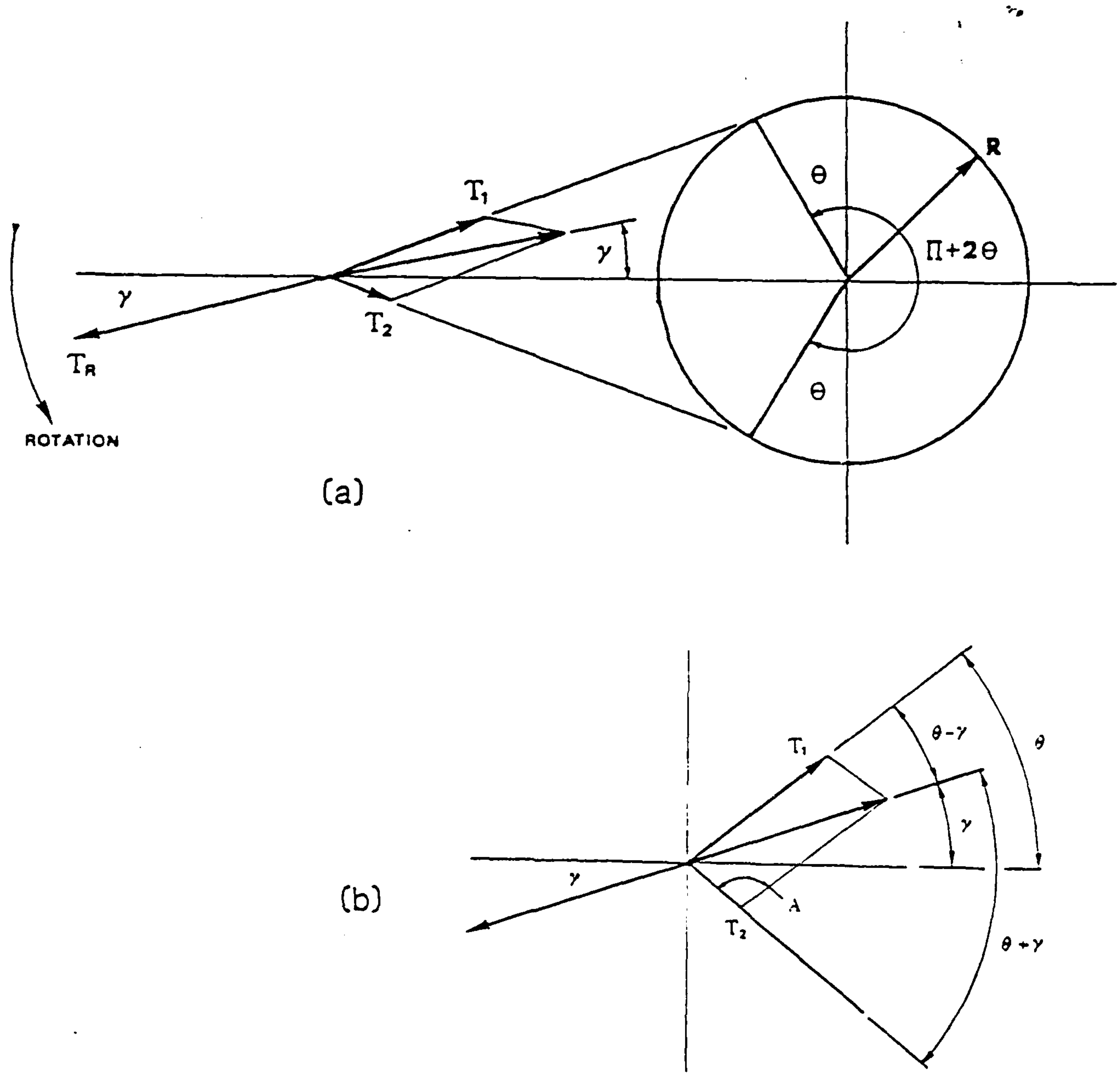


FIGURE 3-1 EYE SPLICE / BOLLARD FORCE DIAGRAM

Substituting equation IV-2 and IV-3 into IV-4,

$$\mu = \frac{1}{\pi - 2\theta} \ln\left[\frac{\sin(\theta + \gamma)}{\sin(\theta - \gamma)}\right] \qquad \text{(IV-5)}$$

4.0 EXPERIMENTAL DESIGN

4.1 Setup

The operational condition being studied is the rotation of the eye around a bollard; because of the configuration of the available test equipment, a test method is used in which the bollard rather than the line rotates. The fixture is shown in Figure 4-1. The eye is placed around the simulated bollard (mounted on a shaft with ball bearings) and tension applied to the line by the hydraulic cylinder at the far end of the test machine (upper left in Figure 4-1). The bollard rotation mechanism consists of a sheave bolted to the bollard with a wire rope wrapped around it and connected to a hydraulic cylinder. The bollard is rotated by actuating the hydraulic cylinder (not shown in Fig. 4-1) which pulls the wire rope turning the sheave and bollard as wire rope is pulled off the sheave.

The surface of the bollard is treated with a metal powder flame spraying technique and dressed to produce a reasonably abrasive surface. This is discussed in more detail in Section 5.6.

Nylon double-braid and 3-strand lines are tested. The inclusion of 3-strand line provides comparison with double-braid; 3-strand was selected because there is considerable 3-strand line in use in the fleet. The dimensions of the samples are:

Line Diameter (d): 7/8 inch

Line sample length: 18 feet

Bollard End:

Bollard Eye length (L): 5'3"
Bollard diameter (D): 10-1/2 inches
Bollard diameter (D)/line diameter (d): 12:1
L/D: 6:1

Pulling End:

Eye length (L): 9 inches
Clevis pin diameter (D): 1-1/2 inches
Clevis pin diameter (D)/line diameter (d): 1.7:1
L/D: 6:1

All 3-strand line splices have five tucks.

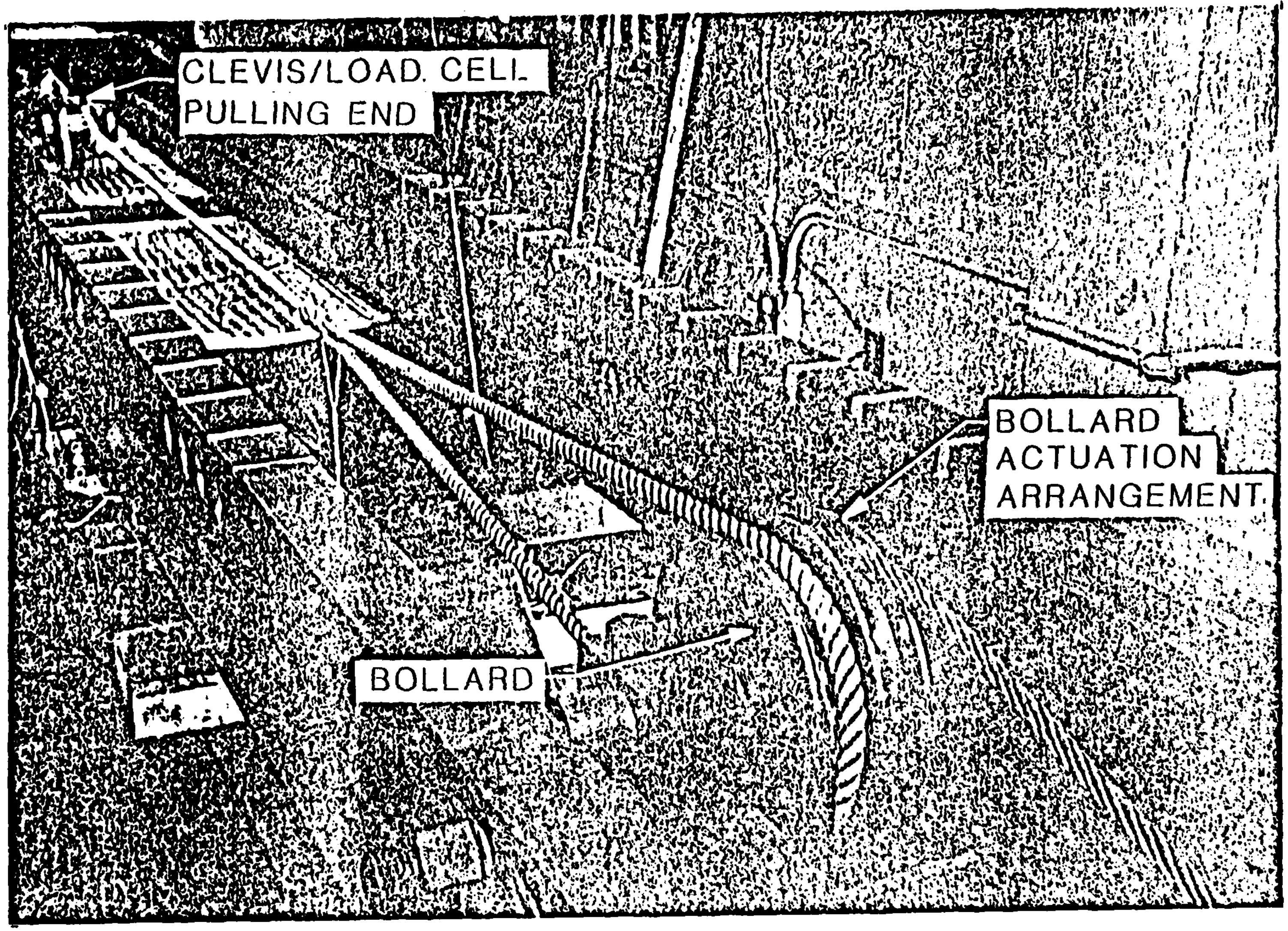


FIGURE 4-1 TEST SETUP

4.2 Data Collection Scheme

Since the tensions in the legs of the eye are calculated from the geometry of the eye with respect to the standing part of the line, the data recording technique used here records the change in configuration due to tensile and rotational loading. The configuration of the test sample at failure is calculated knowing the at-rest configuration and adding the change in configuration during loading. This is accomplished by attaching a cable-actuated potentiometer, commonly called a string pot, to the line sample as shown in Figure 4-2. The string pots measure the following displacements:

String Pot 1: Vertical movement of the eye

String Pot 2: Horizontal movement of the eye

String Pot 3: Horizontal movement of the pulling end of the line

The tension in the line is measured by the load cell. Figure 4-3 shows the final configuration of the line sample at failure and shows what the string pot displacements represent. The results are calculated from the data in the following manner:

X_1: Initial distance from the bollard shaft to the line sample eye

X_2: Horizontal displacement of the eye as a result of applying tension; measured by string pot 2

Y: Vertical displacement of the eye caused by bollard rotation; measured by string pot 1

R: Radius of bollard

$$\theta = \sin^{-1}\left(\frac{R}{\sqrt{(X_1 + X_2)^2 + Y^2}}\right) \qquad \text{(V-1)}$$

$$\phi_2 = \tan^{-1}\left(\frac{Y}{X_1 + X_2}\right)$$

L_1: Initial length of line sample (at rest)

L_2: Horizontal projection of line sample length at failure

$$L_2 = X_3 - L_1 - X_2$$

$$\phi_1 = \tan^{-1}\left(\frac{Y}{L_2}\right)$$

$$\gamma = \phi_1 + \phi_2 \qquad \text{(V-2)}$$

γ : Angle of inclination of the line with respect to the eye.

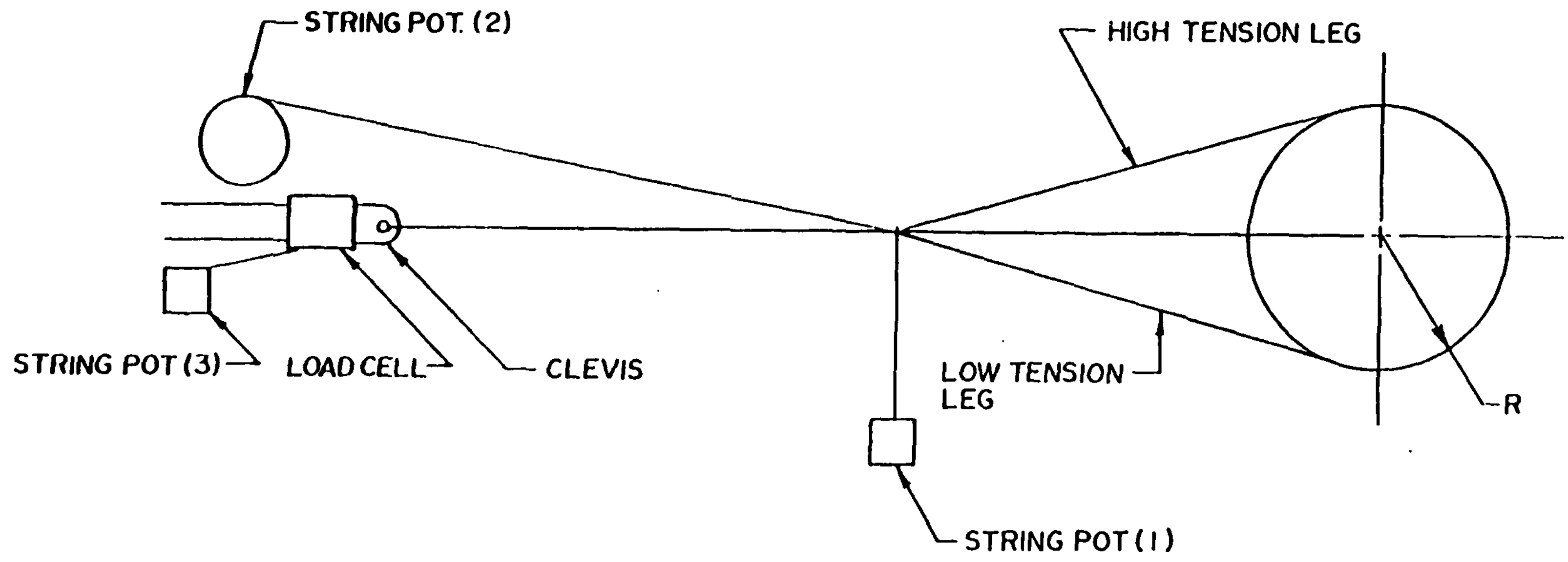


FIGURE 4-2 TRANSDUCER ARRANGEMENT

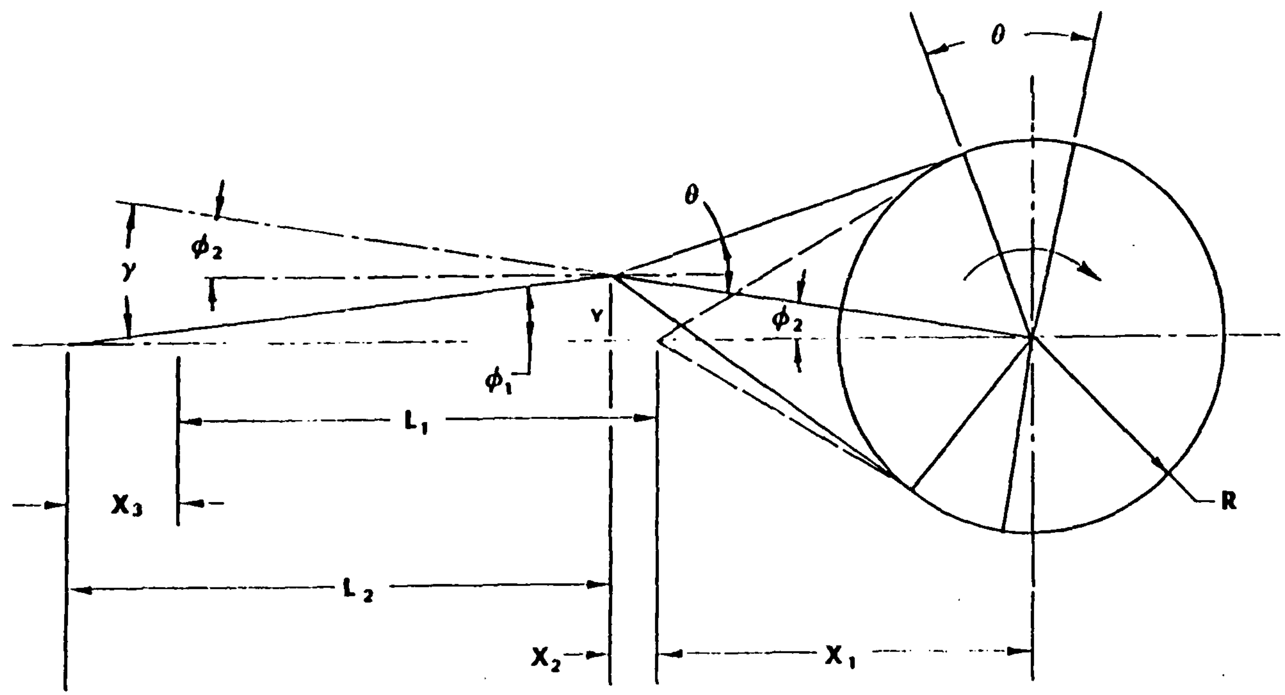


FIGURE 4-3 DATA REDUCTION SCHEMATIC

Knowing the tension in the line, T_R, recorded from the load cell, and the two angles calculated from equation (V-1) and (V-2), the tension in the legs are obtained; for convenience they are:

$$T_1 = T_R \frac{\sin(\Theta - \gamma)}{\sin(\Pi - 2\Theta)} \quad \text{(IV-2)}$$

$$T_2 = T_R \frac{\sin(\Theta - \gamma)}{\sin(\Pi - 2\Theta)} \quad \text{(IV-3)}$$

4.3 Test Procedure

Baseline Tensile Test - A straight pull tensile test determines the strength of the line with no rotational loading. Each line sample is cycled to 20% of rated break strength (RBS) ten times before pulling to failure. Four samples of each line type and splice type are tested.

Rotation Test - Each sample is conditioned to 20% RBS ten times. Then the tension is increased to 60-70% RBS and the bollard rotated. If failure does not occur, the tension is increased further. All test parameters are recorded continuously on strip chart recorders. Each leg of the eye is tested by placing it in the bollard fixture so that the greater portion of the tension is transferred to it as the bollard rotates. Four samples of each leg are tested.

5.0 RESULTS

5.1 Baseline Tensile Strengths

The baseline tensile strengths of the lines tested exceed the minimum rated break strength as required by the specifications (Table 5-1). The Red Book splice is approximately 9.8% stronger than the Blue Book splice.

5.2 Strength of Solices in Rotational Loading

The Red Book splice shows no significant (confidence limit of 90%) strength loss in rotational loading regardless of which leg carries the highest load (Table 5-2).

The Blue Book splice shows no significant strength loss in rotational loading when the insert leg carries the high load. When the standing leg carries the high load, the line can only carry 62% of the rated break strength. This confirms the assertion that the Blue Book splice does have a leg that is much weaker than the rated break strength of the line.

Nylon 3-strand line fails at 81% of the rated break strength when the insert leg carries the highest load. When the standing leg carries the highest load, there is no reduction in strength.

5.3 Failure Descriptions

When the standing leg of the Blue Book splice is rotationally loaded, that leg fails in the area where the insert leg goes into the standing leg (i.e., in the throat of the eye). This is the area where there is no core (refer to Figure 2-1) and only the cover sustains the load. This is shown in Figure 5-1. When the standing leg of the Red Book splice is subjected to rotational loading, failure occurs at the end of the splice taper, or occasionally in the standing leg in the area where the insert leg enters the line. The strength of the line is not reduced.

When the insert leg of the Red Book and Blue Book splices are rotationally loaded, failure occurs near the base of the taper of the splice rather than in the leg. The line retains 100% of its strength (Figure 5-2). Failure at the base of the taper of the splice is the same failure mode as occurs in the straight pull (i.e., no rotation) tensile tests.

Rotational loading of the insert leg of the 3-strand eye does not cause the leg to fail but rather the failure is precipitated in the splice. Two strands in the splice fail (and recoil along the one remaining strand of the standing part of the line) allowing the strands in the insert leg to pull free of the tucks of the splice and come completely free of the line (Figure 5-3). Rotational loading of the standing leg results in the same general type of failure except that the eye does not usually come apart.

5.4 Load Split Between Legs

The results of these tests indicate that the tension in the high tension leg is approximately three times that in the low tension leg. The high-tension side carries a maximum of 75% while the low-tension leg carries the remaining 25%. In an attempt to achieve a much higher load split, tests were conducted at much higher tensions and on a very rough bollard. The part of the eye in contact with the bollard is severely abraded and fails after slipping several times on the bollard. It is difficult to conceive of an operational situation in which conditions would exceed the test conditions and produce much higher load splits.

5.5 Recoil Observations

Lines that fail in the taper of the splice recoil along a path fairly close to the axis of the line and very little snapback volume is covered. When failure occurs in a leg of the eye (as in the standing leg of the Blue Book splice and the insert leg of the 3-strand splice), considerable lateral motion is imparted to the line as the parted end of the eye recoils around the bollard. The snapback volume travelled by the line as it recoils is quite large.

TABLE 5-1. BASELINE TENSILE STRENGTHS

Line		Dia.(in)	Baseline Tensile Strength (lbs)	Rated Break Strength (lbs)	Specification/ Manufacturer
Nylon Double-Braid	Red Book	7/8	26675 (1904)	22,500	MIL-R-24050 Wellington Puritan, Inc.
	Blue Book		24044 (1113)		
Nylon 3-strand twisted		7/8	22764 (2065)	19,000	MIL-R-17343 Columbian Rope Company

Standard Deviations are shown in parenthesis ( ).

TABLE 5-2. ROTATIONAL LOADING TENSILE STRENGTHS

		Baseline Strength, T_o (lbs) (No Rotat.)	High Tension in:	Strength of Line, T_R (lbs) (Rotat.)	$\frac{T_R}{T_o}$(%)	Significant Strength Reduction
Double Braid	Red Book (Revised Method)	26675 (1904)	Insert Leg	25397 (4217)	95.2	NO (1)
			Standing Leg	25789 (1915)	96.5	NO (1)
	Blue Book (Previous Method)	24044 (1113)	Insert Leg	23951 (2070)	99.6	NO (1)
			Standing Leg	14953 (2182)	62.1	YES
3-Strand Twisted		22764 (2065)	Insert Leg	18539 (550)	81.4	YES
			Standing Leg	21968 (2023)	96.5	NO (1)

STANDARD DEVIATIONS ARE SHOWN IN PARENTHESIS ( ).

(1) There is no statistically significant difference (at a 90% confidence limit) between the strength of the line with rotational load, T_R, and the baseline strength, T_o, (no rotation).

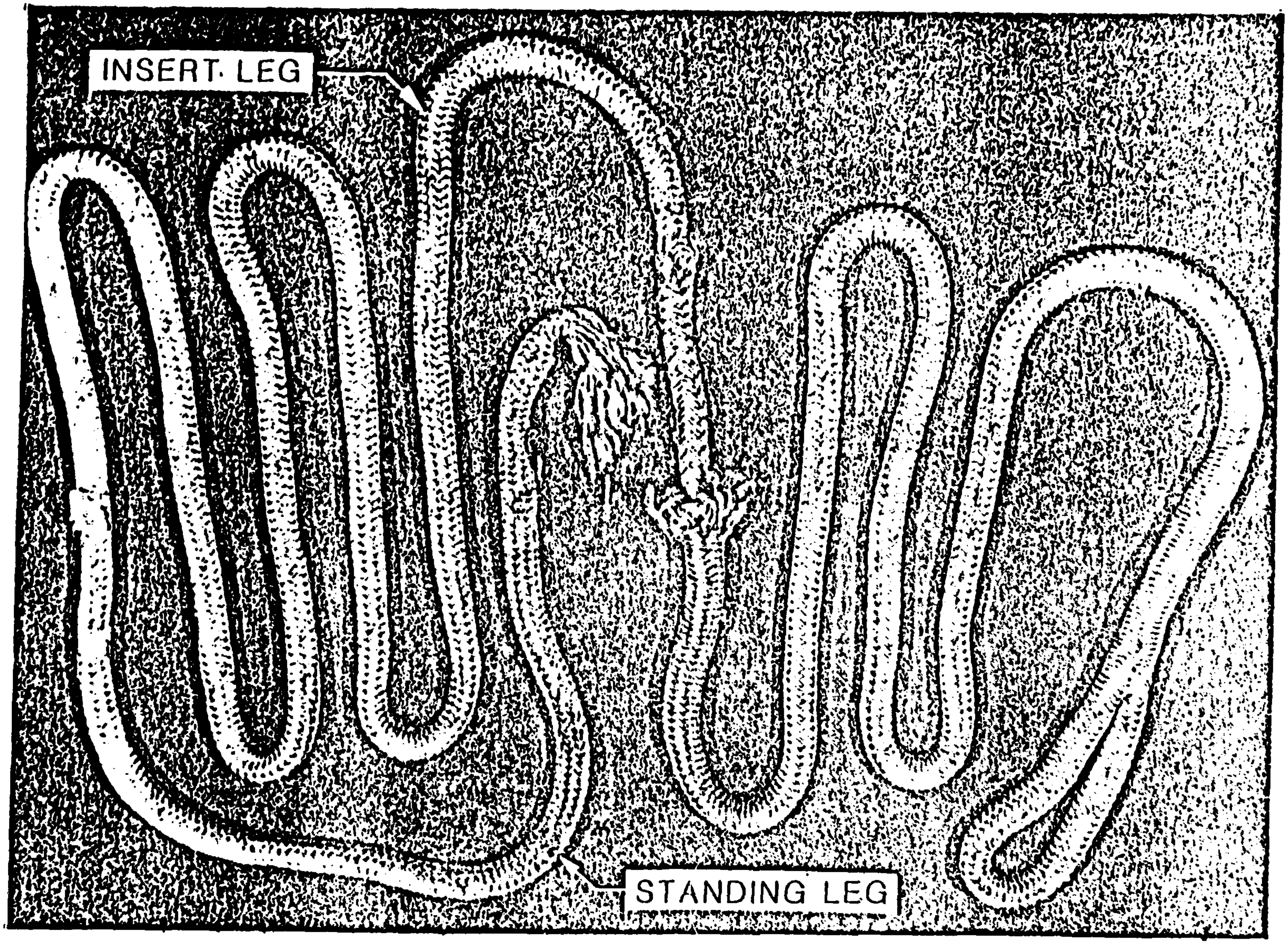


FIGURE 5-1 FAILURE OF STANDING LEG OF THE BLUE BOOK SPLICE

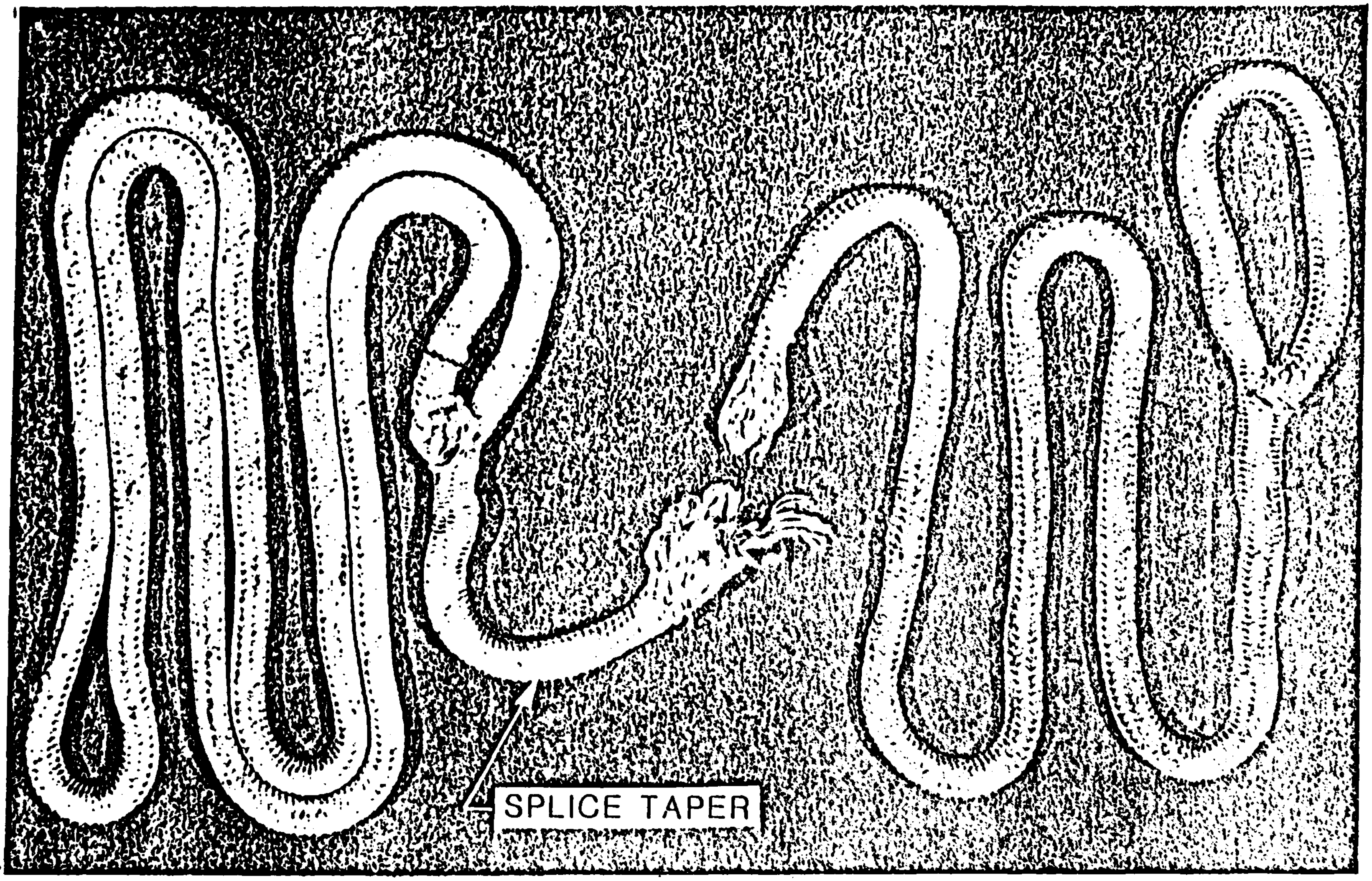


FIGURE 5-2 FAILURE NEAR SPLICE TAPER IN DOUBLE-BRAID LINE

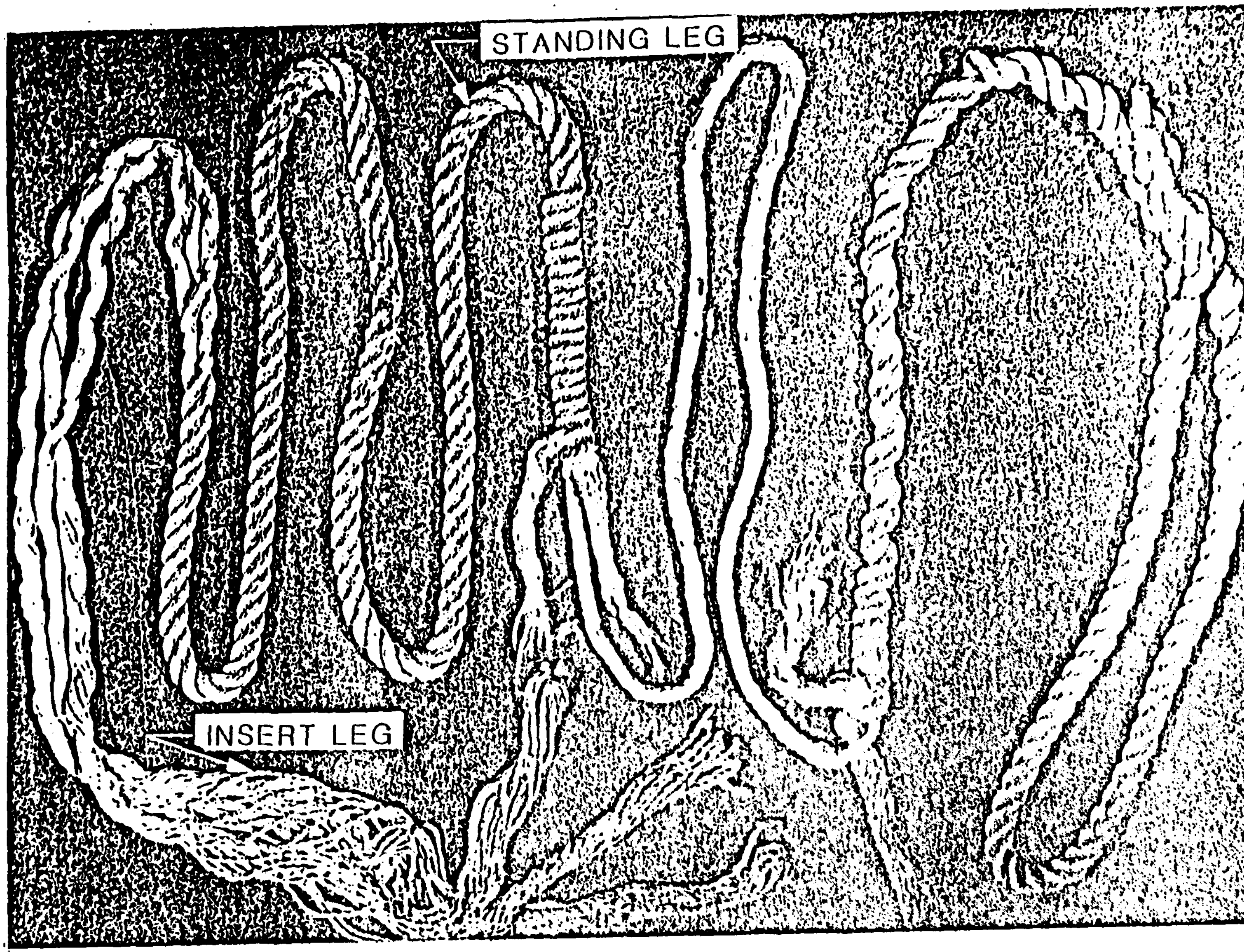


FIGURE 5-3 FAILURE OF 3-STRAND TWISTED LINE EYE SPLICE

5.6 Evaluation of Test Method

The original plan for these tests called for using two bollards with different coefficients of friction. The low-friction bollard (reasonably smooth, as-machined steel), is too smooth and a high enough friction force cannot be developed to transfer tension into one leg to cause failure. Slippage usually occurs before failure. The high-friction bollard is a flame-sprayed surface that is very abrasive. This surface is unsatisfactory also because, if the eye slips before failure more than once, the part of the eye that is in contact with the bollard is ripped out and the eye fails. That bollard, dressed down somewhat to reduce the likelihood of damage to the line, retains enough roughness to develop a high enough friction force to cause one leg of the eye to fail. The coefficient of friction of that surface is approximately .22 as calculated from equation (IV-5).

6.0 CONCLUSIONS

1. The weakness of the standing leg of the Blue Book splice in rotational loading has been confirmed. When that leg is rotationally loaded, the line fails at 62% RBS. When the insert leg is rotationally loaded, the line strength is not reduced.

2. The Red Book splice exhibits no statistical reduction in tensile strength when loaded in rotation.

3. A 3-strand twisted splice, when the insert leg is rotationally loaded, fails at 81% RBS. Failure occurs in the splice rather than in the leg. When the standing leg is rotationally loaded, however, the strength of the line is not significantly reduced.

4. The Red Book splice is approximately 9.8% stronger than the Blue Book splice in straight pull conditions (no rotation).

5. For the conditions of these tests, the maximum load split between the legs of the eye in rotational loading is approximately 3:1. Considering the very rough bollard surface used in these laboratory tests, it is difficult to believe that a larger load split could occur in operational conditions.

6. When failure occurs in the legs of the splice, the fractured end of the eye recoils around the bollard and covers a very substantial snapback volume.

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